GEOPHYSICAL RESEARCH LETTERS, VOL. 34, L14704, doi:10.1029/2007GL030221, 2007

Local and remote contributions to Arctic warming

Drew Shindell[1]

Received 30 March 2007; revised 21 June 2007; accepted 25 June 2007; published 20 July 2007.

[1] I investigate the relative impact of local and remote radiative forcing by tropospheric aerosols and ozone on Arctic climate using GISS climate model simulations. During boreal summer, Arctic climate is well-correlated with either the global or Arctic forcing. During other seasons, however, large-scale dynamics strongly influence the Arctic, so that the surface temperature response follows the global or Northern Hemisphere extratropical forcing much more closely. The decoupling is so strong that Arctic surface temperature trends often show the opposite sign to the local forcing. The analysis also demonstrates that ozone and aerosols affect Arctic climate more strongly per unit global forcing than well-mixed greenhouse gases, typically 2.5–5 times in non-summer seasons, making them powerful levers for influencing Arctic climate. However, controlling atmospheric burdens of climate-altering pollutants outside the polar region appears to be at least as important as controlling them within for mitigation of Arctic warming.
Citation: Shindell, D. (2007), Local and remote contributions to Arctic warming, *Geophys. Res. Lett.*, *34*, L14704, doi:10.1029/2007GL030221.

1. Introduction

[2] The Arctic has warmed more rapidly during recent decades than most parts of the globe, and the impacts have been dramatic. The extent of Arctic sea ice during the summer has decreased by about $^1/_4$ over the past 30 years [*Stroeve et al.*, 2005], and sea ice thickness also appears to have declined substantially [*Rothrock et al.*, 1999]. Long-term measurements show that the seasonal melt area of the Greenland Ice Sheet has been increasing rapidly, by ~7% per decade since 1979 [*Steffen et al.*, 2004]. Observations indicate as much as a doubling of the annual mass loss from Greenland during the past decade, with current annual loss estimated at 80 to 220 km^3 [*Krabill et al.*, 2004; *Luthcke et al.*, 2006; *Rignot and Kanagaratnam*, 2006; *Velicogna and Wahr*, 2005]. The Arctic is also projected to warm more than any other region during the 21st century, with potentially dramatic consequences for vegetation [*Chapin et al.*, 2005] and sea-ice [*Holland et al.*, 2006].

[3] Amplification of global warming in the Arctic is a well-known phenomenon resulting primarily from feedbacks whereby warmer temperatures reduce snow and ice cover, decreasing the Earth's reflectivity (albedo) and thus enhancing warming. While the impact of increasing abundances of well-mixed greenhouse gases (WMGHGs) dominates Arctic warming, short-lived species also play an important role. Aerosols have a large effect on radiative fluxes in the Arctic [*Garrett and Zhao*, 2006; *Lubin and Vogelmann*, 2006], and deposition of black carbon (BC) darkens snow and ice surfaces, also leading to radiative perturbations [*Jacobson*, 2004; *Koch and Hansen*, 2005; *Warren and Wiscombe*, 1980]. Additionally, tropospheric ozone has been shown to play an important role in seasonal Arctic warming trends [*Shindell et al.*, 2006]. These results have led to substantial interest in the role of short-lived species in driving Arctic warming [*Law and Stohl*, 2007; *Quinn et al.*, 2007].

[4] Using climate model simulations of the preindustrial to the present, we examined previously the relative importance of short- and long-lived species [*Shindell et al.*, 2006]. We showed that while increases in WMGHGs clearly dominate annual average Arctic warming, tropospheric aerosols could offset or even outweigh the WMGHGs during the boreal summer. Additionally, both tropospheric ozone and aerosols played substantial roles in non-summer seasons, inducing surface temperature changes of up to 24% and −45%, respectively, of the warming in response to WMGHGs. As these pollutants are inhomogeneously distributed, it is important to understand if their effects on Arctic climate are primarily related to their abundance within the Arctic itself, or if instead the climate system brings the effects of remote pollutants indirectly to the Arctic via heat transport. This has clear implications for climate change mitigation strategies involving air pollutants. Here I address this question through analysis of climate model output, and characterize the utility of metrics that could be employed to estimate the effects of climate or air quality policies on the Arctic.

2. Experimental Setup

[5] I analyze a series of 1880–2003 transient climate simulations performed with the GISS coupled atmosphere-ocean climate model [*Schmidt et al.*, 2006]. These are driven by time-dependent changes in forcings as developed for runs provided to the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) and described in detail by *Hansen et al.* [2007]. Here I examine the response to the following individual forcings: WMGHGs, ozone (both tropospheric and stratospheric), tropospheric aerosol direct effects and tropospheric aerosol indirect effects. Aerosols include changes in sulfate, nitrate and carbonaceous species (sea-salt and dust aerosols were held fixed). The aerosol indirect effect is based on a parameterization of particle influence on cloud cover [*Menon et al.*, 2002]. An ensemble of five runs was performed for each forcing, differing only in their initial conditions. All responses are evaluated using area-weighted ensemble-mean linear trends.

[1]NASA Goddard Institute for Space Studies and Center for Climate Systems Research, Columbia University, New York, New York, USA.

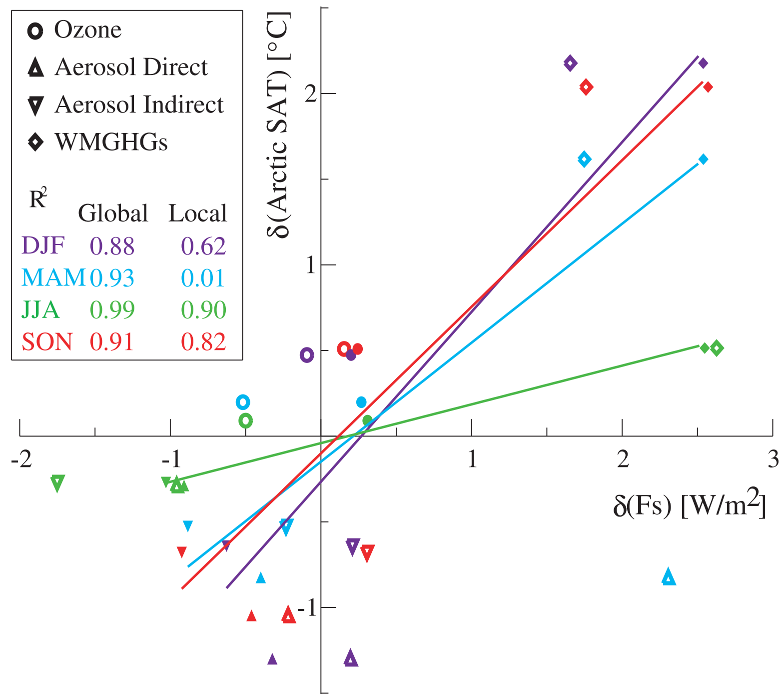

Figure 1. Arctic (68–90 N) surface temperature trends versus global (solid symbols) and local (open symbols) fixed-SST forcing (F_s) in GISS simulations for 1880–2003. Colors indicate the season, shapes the forcing. Lines show seasonal linear fits using global forcings. Correlations for the global and local seasonal fits are given in the inset table. Standard deviation of the ensemble mean temperature trends is ~0.15 C during JJA and ~0.35 to 0.45 C during other seasons, while for the forcing it is only ~0.1 W/m^2, making all points significant other than the spring and summer local and global ozone and winter local ozone results.

[6] The analysis relates the radiative forcing (RF) imposed on the climate model to the Arctic surface air temperature response. To characterize the RF, I use area-weighted means of the fixed-sea surface temperature (SST) forcing (F_s), a measure of radiative imbalance at the top of the atmosphere (TOA) caused by the imposed perturbation after allowing for the adjustment of fast feedbacks (months or less), mainly atmospheric and land temperatures [*Hansen et al.*, 2005]. This forcing thus represents the energy imbalance that drives long-term climate change. This forcing was derived by running the identical climate model with prescribed SSTs and sea ice and the same imposed perturbation, and then calculating the radiative flux change once the model equilibrated (using 90 years of simulation and accounting for any surface temperature response that takes place). This measure of RF is more useful for estimating climate response than the common instantaneous or adjusted tropopause or TOA forcings [*Hansen et al.*, 2005].

3. Results

[7] To assess the importance of local versus remote forcing of the Arctic, I first compare the seasonal Arctic (68–90 N) surface temperature responses with both the local and global forcings (Figure 1). I perform linear fits of the response to the forcing using the 4 forcings discussed previously as independent points. There is a convincing relationship between global forcing and Arctic climate response, with linear least-squares correlations (R^2) greater than 0.88 in all seasons (Figure 1). Sensitivity varies seasonally, maximizing during boreal winter and minimizing during summer. Comparable analyses using other large-area forcing averages, 20–90 N or 20–68 N, show correlations of 0.92–0.94 during DJF and MAM, with values of 0.98–0.99 during JJA and SON, broadly similar to the global forcing results. The correlation between local forcing and response is thus substantially less (0.01 during MAM, 0.6–0.8 during DJF and SON) during all non-summer seasons than that obtained using any of the other broader-area forcings. In contrast, the correlation of surface response with local forcing is 0.90 in boreal summer, nearly as high at the correlation with large-area forcings.

[8] Global climate sensitivity is a widely used metric as it provides a reasonable estimate of the response to a given RF. Analogous to the global climate sensitivity, I define three Arctic climate sensitivities as the Arctic surface temperature response divided by the Arctic, Northern Hemisphere (NH) extratropical (20–90 N), or global forcing, which I call Arctic/local_F_s, Arctic/NH_extratropical_F_s and Arctic/global_F_s sensitivities, respectively. As the sensitivity may vary between forcing agents, linear correlations such as those shown in Figure 1 may be of limited value. Hence I use these new metrics to examine the forcing-response relationship in more detail.

[9] Discrimination between the effects of local and remote forcing is clearest when the forcings have not only different magnitudes but different signs, which occurs for both aerosol and ozone forcing in at least some seasons (hence the choice of total rather than tropospheric ozone, as the latter is positive everywhere while inclusion of stratospheric ozone depletion leads to seasonally negative Arctic

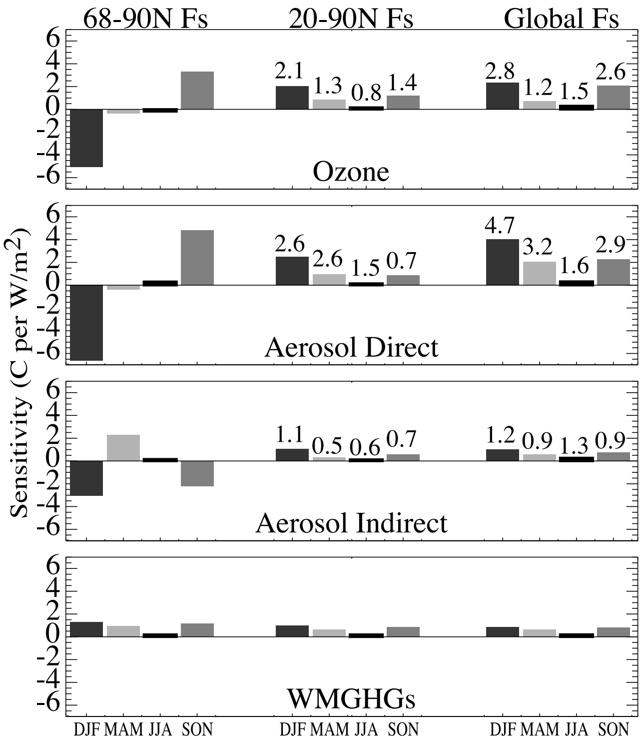

Figure 2. (left) Seasonal Arctic/local_F_s, (middle) Arctic/NH_extratropical_F_s and (right) Arctic/global_F_s sensitivities based on the indicated sets of ensemble simulations. Sensitivity is defined as the model's Arctic (68–90 N) surface temperature trend divided by the imposed forcing (F_s) averaged over the various regions. Numerical values over the bars give the sensitivities for the short-lived species relative to the sensitivity to WMGHGs for the same F_s area-average and season (i.e. the sensitivities are normalized by the values shown in the bars in the bottom row).

forcing). The Arctic/local_F_s sensitivity has a negative value in at least one non-summer season for each of the short-lived species forcings, indicating that the temperature response is opposite to the local forcing (Figure 2). Hence the local forcing would make a very poor metric for estimating the response in the Arctic for these forcings. In contrast, the Arctic/global_F_s and Arctic/NH_extratropical_F_s sensitivities are always physically reasonable (i.e. positive) for the short-lived species (the sensitivity to WMGHGs is reasonable for all cases as this forcing is relatively homogeneous).

[10] The Arctic/global_F_s sensitivity is enhanced for ozone and the direct effect of aerosols in comparison with WMGHGs or aerosol indirect effects (Figure 2). Part of this may be due to the spatial distribution of the forcings. If tropical and SH forcing is less important to the Arctic response (which remains to be shown), using the global RF would effectively dilute the localized NH extratropical forcing. Calculating the temperature change relative to the 20–90 N forcing instead of the global RF brings the sensitivity to ozone and aerosol forcings closer to the sensitivity to WMGHGs (Figure 2). This suggests that indeed the greater 'efficacy' of ozone and aerosols (direct) may be at least partially related to anthropogenic aerosol and tropospheric ozone precursor emissions occurring primarily at NH mid-latitudes (large-scale forcing from ozone is dominated by the troposphere, with <15% contribution from stratospheric ozone changes). Additional enhancements relative to WMGHGs may come from shortwave absorption by ozone and absorbing aerosols, which leads to local heating and hence can affect atmospheric circulation [*Wang*, 2004] and which may be especially important over highly reflective surfaces.

[11] The Arctic/global_F_s and Arctic/NH_extratropical_F_s sensitivities both show a pronounced seasonal cycle with greater values during boreal winter, and to a lesser extent in spring and fall. Seasonal sensitivities have to be interpreted carefully, however. For short-lived species, global mean temperature responses show summer/winter differences of only ~10%, but the imposed RF varies by more than a factor of 3, creating an apparent seasonality in sensitivity on the global scale (global δSAT/F_s). In fact, the forcing varies rapidly, while the global climate responds more slowly and hence in effect integrates the forcing over the annual cycle. Thus for ozone and aerosols, though the global climate sensitivity is close to the sensitivity to WMGHG for the annual average, it is enhanced relative to the annual average during boreal winter when forcing is small and it is reduced during summer. This 'false seasonality' effect likely contributes to the Arctic sensitivity as well since the Arctic is influenced by slow, large-scale climate changes, and it may account for the bulk of the seasonality of the aerosol indirect effect. Arctic sensitivity for ozone and the direct aerosol effect is enhanced even for the annual average, however, and not simply shifted high in some seasons and low in others.

[12] Arctic climate sensitivity varies seasonally partially as a result of strong ice and snow albedo feedbacks. These can be readily activated by short-lived species that are co-located with these feedbacks at NH middle and high latitudes, especially over land. Unlike the WMGHGs, the short-lived species themselves also have very large seasonal variations due to changes in emissions and photochemical lifetimes. Both these factors may contribute to the enhanced seasonality in the Arctic climate sensitivity to short-lived species.

4. Discussion and Conclusions

[13] Among the most striking results are that the Arctic cools during Dec–Feb in response to changing aerosols even though the RFs from both the direct and indirect effects are positive in the Arctic (both are negative when averaged globally or over the NH extratropics). The positive direct aerosol forcing in the Arctic results from absorption of longwave terrestrial radiation by aerosols. The absorption of incoming or reflected sunlight by BC may also contribute, and may have a rather unique effect in the Arctic, where it could provide a positive TOA RF while at the same time reducing sunlight available at the surface to melt snow or ice [*Wang*, 2004]. Given the very limited sunlight during polar winter, however, we expect shortwave effects to be small (though they may be large during spring, when the direct aerosol effect in the Arctic is strongly positive, yet the surface again cools). In contrast, the longwave aerosol effect appears to be quite large during winter. Hence the locally positive direct aerosol forcing in the Arctic during winter

should induce local warming. The cooling that is seen instead is thus a clear demonstration that the local forcing is outweighed by remote forcing.

[14] Similarly, as aerosol abundances grew during the 20th century, the indirect aerosol effect led to increased cloud cover. Globally averaged, this caused negative forcing in all seasons as the clouds reflect solar radiation to space. In the Arctic, however, there is little incoming solar radiation during boreal winter and hence the longwave absorption properties of the clouds dominate, leading to a positive forcing in observations [*Garrett and Zhao*, 2006; *Lubin and Vogelmann*, 2006] that is likewise present in the model. Again this should induce a local warming, but again the Arctic temperature response is opposite to the local forcing (which is also the case in spring for the direct effect and fall for the indirect effect).

[15] A similar result is seen in the response to ozone changes. In this case, depletion of stratospheric ozone at high-latitudes outweighs increasing tropospheric pollution, leading to negative Arctic RF during winter, spring and summer (though the winter value is only marginally statistically significant). Despite this, the Arctic surface warms during these seasons (though the spring and summer warmings are not statistically significant). Again this is consistent with the remote forcing (global or NH extratropical) which is positive due to increased tropospheric ozone. Thus it seems that in non-summer seasons, and perhaps even in summer, Arctic climate is closely coupled to extrapolar forcing.

[16] This does not mean that the Arctic will not also respond to local forcing, but that for the historical changes in short-lived species examined here, the remote forcing dominates over the local. This is true for cases in which the absolute value of the local forcing was larger than the opposing remote forcing as well as cases in which it was smaller. While the local Arctic forcing is thus a poor metric for estimating the Arctic climate response, this is not inherently the case for regional metrics. An analogous calculation for the tropics indicates that the tropical forcing is of comparable utility to the global forcing in predicting the tropical response.

[17] During summer, when local radiative processes play a major role in surface temperatures, the local Arctic forcing is roughly as good a predictor of Arctic response as the remote forcing. During non-summer seasons, however, the small amount of incoming radiation and the strong temperature gradients between the Arctic and lower latitudes appear to make it especially sensitive to climate changes in other areas which can be dynamically communicated to the polar region. This idea can be tested by investigating the unforced Arctic warming of the 1930s and 40s, which has been linked to changes in atmospheric and oceanic dynamics [*Delworth and Knutson*, 2000; *Johannessen et al.*, 2004]. Examining the peak 1935–1945 anomaly relative to a 1951–1980 baseline in the GISS land-ocean surface temperature dataset [*Hansen et al.*, 2001], I find that boreal summer warming was only $\sim$0.1–0.2 C in the Arctic, compared with non-summer warming of more than a degree. Thus the warming during this episode is consistent with a strong dynamical influence in non-summer months only. While it is clear that large-scale dynamics strongly influences non-summer transport of mid-latitude pollution to the Arctic [*Eckhardt et al.*, 2003], these results suggest that mid-latitude pollutants may also influence large-scale dynamics (via changes in oceanic and/or atmospheric circulation and/or in latent and sensible heat content), facilitating an impact of remote pollutants on the Arctic.

[18] The effect of BC on snow and ice albedo is clearly most important at high latitudes, and especially in the Arctic. In comparable GISS climate model simulations, this effect contributes 0.2–0.5 C (depending on season) to the 1880–2003 warming of the Arctic [*Hansen et al.*, 2007]. This effect was not included in these analyses as the conclusion is obvious, namely that since the forcing is almost exclusively at high latitudes, the Arctic response is highly correlated with the local forcing. Thus BC emissions that eventually reach the Arctic are of particular concern. As discussed above, the enhanced non-summer sensitivity of the Arctic to ozone and direct aerosol effects also seems to stem partially from their emissions coming predominantly from NH mid-latitudes, indicating that the location of emissions of short-lived precursors does matter.

[19] I also note that the simple formulation of the aerosol indirect effect used in our model allowed aerosols to affect only cloud cover via cloud droplet number concentration, and included only liquid-phase stratus clouds and not ice-clouds. More generally, aerosol-cloud-radiation interactions in the Arctic are not fully understood [*Quinn et al.*, 2007], and thus additional aerosol indirect effects that were not included here could substantial affect local forcing. Further work in assessing the value of Arctic forcing metrics using surface forcing is also warranted, as the opposing surface and TOA forcings from absorbing species such as BC could account for a portion of the mismatch between local forcing and response using TOA forcing (e.g. during MAM for aerosol direct). However, as noted previously, this should not greatly affect the winter results, which are dominated by longwave rather than shortwave forcing at high-latitudes, as shown for ozone by *Shindell et al.* [2001] and for the aerosol indirect effect by *Lubin and Vogelmann* [2006].

[20] This study shows that though local composition changes can be important to Arctic climate, the warming there to date has likely been driven largely by trends outside the Arctic, even for the portion from short-lived species. This is most clearly the case in the non-summer seasons, when the warming has been greatest [*Hansen et al.*, 2001; *Shindell et al.*, 2006]. It appears that atmospheric and oceanic mixing cause the Arctic to generally follow global or hemispheric forcing during boreal spring, winter and fall. The implications of this study for climate change due to short-lived species are twofold. First, the sensitivity of Arctic climate to short-lived pollutants is enhanced roughly 3–5 times relative to WMGHGs during boreal winter and fall, and $\sim$1.2–3 times during spring and summer. Thus reducing NH emissions of ozone and perhaps absorbing aerosol precursors offers strong leverage for moderating Arctic warming. Conversely, reductions in reflective aerosols may strongly enhance Arctic warming, and would thus require compensating reductions in warming agents such as WMGHGs to stave off additional Arctic warming. Second, while controls on emissions that lead to forcing within the Arctic are certainly desirable, slowing the dramatic warming there will require mitigation of RF from short-lived species over a much larger area.

[21] **Acknowledgments.** NASA's Atmospheric Chemistry Modeling and Analysis Program supported this work. I am grateful for scientific computing by Reto Reudy, Ken Lo, and Howard Teich.

References

Chapin, F. S., III., et al. (2005), Role of land-surface changes in Arctic summer warming, *Science*, *310*, 657–660.

Delworth, T. L., and T. R. Knutson (2000), Simulation of early 20th century global warming, *Science*, *287*, 2246–2250.

Eckhardt, S., et al. (2003), The North Atlantic Oscillation controls air pollution transport to the Arctic, *Atmos. Chem. Phys.*, *3*, 1769–1778.

Garrett, T. J., and C. Zhao (2006), Increased Arctic cloud longwave emissivity associated with pollution from mid-latitudes, *Nature*, *440*, 787–789.

Hansen, J., R. Ruedy, M. Sato, M. Imhoff, W. Lawrence, D. Easterling, T. Peterson, and T. Karl (2001), A closer look at United States and global surface temperature change, *J. Geophys. Res.*, *106*, 23,947–23,963.

Hansen, J., et al. (2005), Efficacy of climate forcings, *J. Geophys. Res.*, *110*, D18104, doi:10.1029/2005JD005776.

Hansen, J., et al. (2007), Climate simulations for 1880–2003 with GISS modelE, *Clim. Dyn.*, doi:10.1007/s00382-00007-00255-00388, in press.

Holland, M. M., C. M. Bitz, and B. Tremblay (2006), Future abrupt reductions in the summer Arctic sea ice, *Geophys. Res. Lett.*, *33*, L23503, doi:10.1029/2006GL028024.

Jacobson, M. Z. (2004), Climate response of fossil fuel and biofuel soot, accounting for soot's feedback to snow and sea ice albedo and emissivity, *J. Geophys. Res.*, *109*, D21201, doi:10.1029/2004JD004945.

Johannessen, O. M., et al. (2004), Arctic climate change: Observed and modeled temperature and sea-ice variability, *Tellus Ser. A.*, *56*, 328–341.

Koch, D., and J. Hansen (2005), Distant origins of Arctic black carbon: A Goddard Institute for Space Studies ModelE experiment, *J. Geophys. Res.*, *110*, D04204, doi:10.1029/2004JD005296.

Krabill, W., et al. (2004), Greenland Ice Sheet: Increased coastal thinning, *Geophys. Res. Lett.*, *31*, L24402, doi:10.1029/2004GL021533.

Law, K. S., and A. Stohl (2007), Arctic air pollution: Origins and impacts, *Science*, *315*, 1537–1540.

Lubin, D., and A. M. Vogelmann (2006), A climatologically significant aerosol longwave indirect effect in the Arctic, *Nature*, *439*, 453–456.

Luthcke, S. B., H. J. Zwally, W. Abdalati, D. D. Rowlands, R. D. Ray, R. S. Nerem, F. G. Lemoine, J. J. McCarthy, and D. S. Chinn (2006), Recent Greenland ice mass loss by drainage system from satellite gravity observations, *Science*, *314*, 1286–1289.

Menon, S., A. D. Del Genio, D. Koch, and G. Tselioudis (2002), GCM simulations of the aerosol indirect effect: Sensitivity to cloud parameterization and aerosol burden, *J. Atmos. Sci.*, *59*, 692–713.

Quinn, P. K., G. Shaw, E. Andrews, E. G. Dutton, T. Ruoho-Airola, and S. T. Gong (2007), Arctic haze: Current trends and knowledge gaps, *Tellus, Ser. B*, *59*, 99–114.

Rignot, E., and P. Kanagaratnam (2006), Changes in the velocity structure of the Greenland Ice Sheet, *Science*, *311*, 986–990.

Rothrock, D. A., Y. Yu, and G. A. Maykut (1999), Thinning of the Arctic sea-ice cover, *Geophys. Res. Lett.*, *26*, 3469–3472.

Schmidt, G. A., et al. (2006), Present day atmospheric simulations using GISS ModelE: Comparison to in-situ, satellite and reanalysis data, *J. Clim.*, *19*, 153–192.

Shindell, D. T., J. L. Grenfell, D. Rind, C. Price, and V. Grewe (2001), Chemistry-climate interactions in the Goddard Institute for Space Studies general circulation model: 1. Tropospheric chemistry model description and evaluation, *J. Geophys. Res.*, *106*, 8047–8076.

Shindell, D., G. Faluvegi, A. Lacis, J. Hansen, R. Ruedy, and E. Aguilar (2006), Role of tropospheric ozone increases in 20th-century climate change, *J. Geophys. Res.*, *111*, D08302, doi:10.1029/2005JD006348.

Steffen, K., S. V. Nghiem, R. Huff, and G. Neumann (2004), The melt anomaly of 2002 on the Greenland Ice Sheet from active and passive microwave satellite observations, *Geophys. Res. Lett.*, *31*, L20402, doi:10.1029/2004GL020444.

Stroeve, J. C., M. C. Serreze, F. Fetterer, T. Arbetter, W. Meier, J. Maslanik, and K. Knowles (2005), Tracking the Arctic's shrinking ice cover: Another extreme September minimum in 2004, *Geophys. Res. Lett.*, *32*, L04501, doi:10.1029/2004GL021810.

Velicogna, I., and J. Wahr (2005), Greenland mass balance from GRACE, *Geophys. Res. Lett.*, *32*, L18505, doi:10.1029/2005GL023955.

Wang, C. (2004), A modeling study on the climate impacts of black carbon aerosols, *J. Geophys. Res.*, *109*, D03106, doi:10.1029/2003JD004084.

Warren, S. G., and W. J. Wiscombe (1980), A model for the spectral albedo of snow. II: Snow containing atmospheric aerosols, *J. Atmos. Sci.*, *37*, 2734–2745.

D. Shindell, NASA Goddard Institute for Space Studies and Center for Climate Systems Research, Columbia University, 2880 Broadway, New York, NY 10025, USA. (dshindell@giss.nasa.gov)